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DROUGHT CLASSIFICATIONS AND A STUDY OF DROUGHTS AT KEW

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SUMMARY

Four objective methods of drought analysis are presented. Two are essentially based on meteorological parameters, one is based on hydrologically effective rainfall (defined in a simple manner) and the fourth is a very simple model for grassland drought. The various droughts (30 days' duration or longer) which occurred at Kew in the period 1871–1975 are ranked, using the four indices, and the more outstanding examples are briefly compared and described.

1. INTRODUCTION

There is no universally agreed definition of drought although the word is associated with rainfall deficiencies over more or less prolonged periods. Numerous indices of drought have been devised by meteorologists, hydrologists, agriculturists, geographers and others for specific purposes and to suit the climatology of particular parts of the world. Hounam *et alii* (1975) review the subject from a broad base, albeit with an agricultural bias, and give a comprehensive list of references.

In this paper emphasis is placed firstly on regarding drought as a relative phenomenon and secondly on relating it to a particular water use. Drought could be said to occur whenever the local water supplies of a district fall below the level associated with the more common fluctuations. Absolute values may be used to measure the severity of a drought, but these do not always enable comparisons with other areas to be readily made. Normally, however, such comparisons are required and relative measures must then be used. When a water deficiency is expressed in terms of an average no account is taken of difference in the variability of rainfall from place to place. Water usages may be expected to be geared to variability of supply. Management techniques in an area of high rainfall variability are generally more flexible than those in areas with more reliable rainfall. A practical way of including the effects of rainfall variability is to relate the severity of a drought to its return period, although simple ranking is used in the illustrative, single-station analysis for Kew.

Drought should also be related to water use. Agriculture is chiefly concerned with adequate summer rain to offset the evaporation and transpiration which occurs in that season. On the other hand, hydrological interests lie much more with winter rain which provides run-off for reservoirs and percolation to recharge aquifers. It seems sensible, therefore, to describe 'hydrological' drought and 'agricultural' drought separately. Various workers, notably Palmer (1961, 1965) have tried to combine these two types of water demand and hence to produce an overall measure of drought severity. In view of the great difference between hydrological and agricultural drought it is doubtful whether an assessment based on the mean of both has any special value. Physical considerations alone, unrelated to water usage, lead to a definition of 'meteorological' drought based only on meteorological parameters.

2. 'Meteorological' drought

A simple measure of 'meteorological' drought (D_m) is the fractional deviation of rainfall (R) from the average ($\bar{R}$),

i.e. $$D_{m,1} = (R - \bar{R})/\bar{R}. \quad .. \quad .. \quad .. \quad (1)$$

In order to obtain a more accurate representation of the water balance, the effects of evaporation (taken to include transpiration) should be included. The potential evaporation (E_p) is the evaporation which takes place when the water supply is unrestricted. As such it is dependent only upon meteorological elements (radiation, temperature, wind and humidity), and hence is suitable for inclusion in a parameterization of 'meteorological' drought. Equation (1) can be modified to include the effects of E_p by writing

$$D_{m,2} = [(R - E_p) - (\bar{R} - \bar{E}_p)]/\bar{R}. \quad .. \quad .. \quad (2)$$

In winter E_p does not depart significantly from mean values whereas in summer large deviations from average may occur. Hence the evaporation terms in equation (2) have much more effect in summer than in winter. For comparing 'meteorological' droughts which occur in the same seasons $D_{m,2}$ should be used. For comparing 'meteorological' droughts occurring in different seasons $D_{m,1}$ is to be preferred since ($E_p - \bar{E}_p$) can be much larger in a summer month than in a winter month and for a given rainfall deficiency a summer-month $D_{m,2}$ value is likely to be more extreme than a winter-month value.

3. A simple measure of 'hydrological' drought

Hydrologists in the UK are interested in adequate winter rains to fill reservoirs and recharge aquifers. The hydrologically effective rainfall (R_e) for such purposes is the water surplus remaining after evaporation has taken place and any soil moisture deficit has been removed. R_e is therefore a possible measure of 'hydrological' drought

i.e. $$D_h = R_e. \quad .. \quad .. \quad .. \quad .. \quad (3)$$

In order to calculate R_e it is necessary to model the departure of the actual rate of evaporation from the potential rate under conditions of soil moisture stress. In the present study, for simplicity, the root-constant concept of Penman (1949), as used by Grindley (1967) in the *Meteorological Office Soil Moisture Deficit Bulletin*, is employed. All the soil moisture lying within the rooting depth of a plant is transpired at the potential rate, and this amount of water,

expressed as equivalent depth of rainfall, is the 'root constant'. In the model a further 0·8 inch (20·3 mm) of water are then allowed to be transpired at the potential rate before the ratio of actual to potential evaporation falls to a value of one-twelfth. In this paper a root constant of 3 inches, generally considered appropriate for grass, is used.

R_e is extremely seasonal in character, mostly occurring during winter, and water resources should be geared to withstand a long period of water depletion during the summer. To a first approximation, therefore, 'hydrological' drought may be regarded as a problem of deficiency of annual R_e. For this purpose the calendar year is unsuitable and the 12-month period from July to June is adopted here.

Hydrological interests are sensitive to R_e summed over more than one year; an excess or deficiency of R_e in any given year will be carried over to subsequent years. In Section 6 of this paper, in which comparisons of 'hydrological' drought at Kew are made, durations of up to 3 years are considered.

4. A SIMPLE MEASURE OF 'GRASSLAND' DROUGHT

Agricultural drought (D_a) is a general term covering a wide range of cases. Every crop has its own drought-sensitive periods, and a proper analysis should treat each crop separately. Grass, however, covers about 70 per cent of agricultural land in this country, and so in this paper attention is limited to grass.

The effects of agricultural drought in agriculture are felt mainly through the associated reduction in crop yield. For grass, crop yield may be related to plant growth, and this is reduced when the supply of either water or nutrients to the plant is restricted. The nutrients are mostly contained in the topmost layers of soil, where the most accessible soil water is also held. It follows that plant growth becomes restricted when the availability of water from the upper layers of soil becomes restricted. A possible measure of 'grassland' drought is therefore

$$D_a = E_p - E_g, \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (4)$$

where E_g is defined as the evaporation (transpiration) effective for growth, and can be associated with water which has been mainly derived from the topmost layers of soil. In this paper, E_g has been obtained from E_p by using a 1 inch (25·4 mm) root constant. In Section 6, comparisons are made for $(E_p - E_g)$ summed over a whole year.

5. LIMITATIONS OF THE PRESENT ANALYSIS

It must be emphasized that the measure of 'hydrological' and 'grassland' drought proposed here are tentative and simple in character. In equations (3) and (4), D_h and D_a are expressed in absolute units and, for a drought of given return period, will take values which depend mainly upon the mean rainfall of the station under consideration. In order to obtain meaningful values of D_h and D_a meaned over an area, it would be necessary to derive expressions from which the dependence on mean rainfall has been removed. Such expressions would be rather complex, however, and as in Section 6, only results from a single station are considered, the simple equations using absolute units having been retained.

In the comparison of droughts made in Section 6, no attempt is made to calculate their return periods. The droughts in a given record are ranked in order of decreasing severity, and these rankings are then compared with one another.

6. Comparison of droughts at Kew over the period 1871–1975

Daily rainfalls have been recorded at Kew since 1871 but monthly averages of all the data required by the Penman formula for potential evaporation are only available from October 1876 onwards. Approximations to Penman potential evaporation prepared by Wales-Smith (1973) have been used for the period January 1871 to September 1876. Daily values of potential evaporation were estimated by apportioning monthly totals in accordance with the elevation of the sun. A complete analysis of 'meteorological', 'hydrological' and 'grassland' drought was made in the manner already described. The mean monthly values of rainfall and potential evaporation at Kew over the period 1871–1975 are given in Table I.

Table I—Mean monthly rainfall and potential evaporation (E_p) at Kew from 1871 to 1975

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Mean rainfall (mm)	50·0	38·9	39·3	42·2	44·9	50·5	59·3	57·7	52·8	60·2	61·1	53·8	610·7
Mean E_p (mm)	6·6	14·1	32·3	55·5	83·2	97·4	99·2	80·6	47·6	21·2	7·5	4·5	549·7

The ten most severe, independent (non-overlapping) 'meteorological' droughts ($D_{m,1}$ and $D_{m,2}$) corresponding to 12 chosen durations ranging from 30 days to 36 months, are presented in Tables II and III. For durations of 30 to 90 days daily rainfalls were analysed and droughts were allowed to start on any day of the month. For durations of four months or more only calendar-month data were analysed and the droughts were measured from the first day of the starting month. The 'non-overlapping' ranks were obtained from a list of droughts which were not allowed to overlap one another. The 'overlapping' rank was obtained from a list of droughts, each of which, to be counted, had to start within a different calendar month from the others. The averages from which the deviations are quoted are those for the period 1871–1975 (see Table I).

The ten most severe 'hydrological' and 'grassland' droughts (D_h and D_a respectively) are presented in Tables IV and V. The ranks were obtained from a list of droughts, each of which had to start in a different year. For 'hydrological' drought lasting over a winter, the year quoted corresponds to the first half of the season. Thus an entry for the year 1947 refers to the winter of 1947–48. For droughts assessed over more than a year the starting date is given. Thus for 'hydrological' drought measured over three years an entry of 1962 refers to the winters of 1962–63, 1963–64 and 1964–65.

Table VI lists the rankings of the more notable droughts of various types at Kew during the period 1871–1975. Each drought is identified loosely by the year in which the driest weather occurred. The Table enables the main characteristics of each drought to be readily identified and compared with others. A brief commentary on each of the listed droughts is given below.

1890

The winter of 1890–91 was one of considerable meteorological interest, and is described by Brodie (1891). The dry weather lasted from September 1890 to April 1891, and gave rise to a typical 'hydrological' drought. Over an eight-month period the rainfall deficiency ranks as the second most severe in the period under consideration, but as a result of the drought occurring during

winter, when E_p seldom departs much from average, its position drops to sixth when $(R - E_p)$ is used as a basis for comparison. The summers of 1890 and 1891 being wet, there was no 'grassland' drought, but the winter of 1890–91 was one of four which failed to record any R_e.

1893

In contrast the summer of 1893, described by Brodie (1894), represents a typical 'grassland' drought. The dry weather encompassed the period March to September and the rainfall deficiency over 75 days starting in early March was the most severe ever recorded over that length of time. The March to September rainfall deficiency ranks seventh over a period of seven months, and when E_p is taken into account it rises to fourth. Since the dry weather spanned the summer half-year a 'grassland' drought ensued, and this stands as the third most severe on record.

1895–1902

The period from 1895 to 1902 was one of protracted dryness. The central portion, in 1897 and 1898, is described by Brodie (1899). For 'meteorological' drought based on $(R - E_p)$, the first six months of 1895 rank ninth, the 24 months starting in October 1897 rank fifth, and the 36 months starting in May 1899 rank second. The winters of 1897 and 1901 both enter the rankings for 'hydrological' drought, and the summer of 1899 stands as the ninth most severe 'grassland' drought. It is over a long period of time, however, that the drought becomes oustanding—for five years starting in May 1897 the rainfall was 20 per cent deficient, and R_e summed over the winters 1897–98 and 1902–03 was the second lowest recorded over a period of five years.

1921

The drought of 1921 is the most famous of all 'meteorological' droughts this century, and is described by Brooks and Glasspoole (1922). Maximum severity was attained over a period of about 12 months comprising the calendar year of 1921, but a glance at Table VI reveals how this drought dominates a wide range of time scales. The associated 'hydrological' and 'grassland' effects are, however, less outstanding. The 'grassland' drought of 1921 was surpassed by that of 1959, while the most severe 'hydrological' effects are obtained over a duration of three years, when the winters of 1919–20, 1920–21 and 1921–22 gave the third lowest total of R_e to be observed.

1933

The period of dry weather occurring around 1933, described by Glasspoole (1935), is remembered chiefly for its 'hydrological' effects. Maximum 'meteorological' severity occurred over a period of 24 months starting in November 1932. The rainfall deficiency stands as the worst on record over a period of 24 months, although when E_p is taken into account it ranks second. 'Grassland' effects were moderate, with the summer of 1933 ranking tenth, but the winter of 1933–34 was one of four when no R_e occurred, and R_e summed over the winters of 1933–34 and 1934–35 was the second lowest ever for a period of two years.

1938

The dry spell which occurred between February and July 1938 represents the most severe rainfall deficiency on record over a period of six months.

TABLE II—'METEOROLOGICAL' DROUGHT AT KEW FROM 1871 TO 1975:

$$D_{m,1} = (R - \bar{R})/\bar{R}$$

Duration of drought

Non-o'lapping Rank	30 days			60 days			90 days			4 months		
	Starting Date	$D_{m,1}$	O'lapping Rank	Starting Date	$D_{m,1}$	O'lapping Rank	Starting Rank	$D_{m,1}$	O'lapping Rank	Starting Date	$D_{m,1}$	O'lapping Rank
1	10 Apr 1942	−1·000	1	27 Jun 1921	−0·951	1	1 Feb 1938	−0·861	1	May 1921	−0·723	1
2	20 Feb 1953	−1·000	2	6 Mar 1893	−0·943	2	30 May 1921	−0·856	2	Mar 1938	−0·713	2
3	14 Aug 1959	−1·000	3	31 Aug 1969	−0·937	3	6 Aug 1947	−0·765	6	Aug 1947	−0·694	4
4	23 Aug 1929	−0·998	4	3 Feb 1929	−0·906	7	1 Oct 1879	−0·753	7	Feb 1956	−0·670	6
5	14 Sep 1921	−0·995	5	1 Mar 1938	−0·897	8	1 Jan 1929	−0·748	9	Oct 1879	−0·668	7
6	20 May 1934	−0·992	6	14 Aug 1959	−0·884	10	5 Aug 1969	−0·748	10	Jul 1972	−0·667	8
7	4 Jun 1949	−0·991	7	21 Jan 1932	−0·865	11	10 Jun 1972	−0·747	11	Nov 1933	−0·666	9
8	18 Apr 1896	−0·986	3	16 Feb 1943	−0·861	12	17 Dec 1972	−0·747	12	Jan 1929	−0·651	11
9	1 Mar 1929	−0·984	9	19 Jul 1947	−0·855	13	2 Nov 1933	−0·732	15	Jun 1959	−0·608	17
10	11 Jun 1941	−0·983	11	9 Jul 1972	−0·850	14	9 Nov 1953	−0·730	16	Mar 1893	−0·601	18

Duration of drought

Non-o'lapping Rank	5 months			6 months			9 months			12 months		
	Starting Date	$D_{m,1}$	O'lapping Rank	Starting Date	$D_{m,1}$	O'lapping Rank	Starting Date	$D_{m,1}$	O'lapping Rank	Starting Date	$D_{m,1}$	O'lapping Rank
1	Feb 1938	−0·728	1	Feb 1938	−0·692	1	Feb 1921	−0·596	1	Jan 1921	−0·495	1
2	Jun 1921	−0·680	2	May 1921	−0·647	2	Jun 1972	−0·514	4	Apr 1972	−0·485	3
3	Jun 1972	−0·665	4	May 1972	−0·634	4	Oct 1933	−0·473	10	Oct 1897	−0·416	11
4	Jul 1947	−0·633	6	Jan 1929	−0·570	8	Aug 1890	−0·462	12	Jul 1933	−0·413	12
5	May 1959	−0·624	7	Sep 1890	−0·567	9	Feb 1959	−0·459	13	Jul 1955	−0·350	26
6	Oct 1933	−0·603	10	Dec 1873	−0·548	12	Jan 1929	−0·451	14	Oct 1948	−0·348	28
7	Jan 1929	−0·574	12	May 1959	−0·547	13	Feb 1938	−0·429	21	Jun 1933	−0·338	30
8	Feb 1895	−0·570	13	Jul 1947	−0·533	16	Dec 1873	−0·425	22	Nov 1928	−0·322	35
9	Oct 1890	−0·537	20	Jan 1895	−0·515	17	Nov 1943	−0·412	25	Nov 1958	−0·313	—
10	Feb 1956	−0·539	21	Oct 1879	−0·513	18	Oct 1879	−0·409	26	Jul 1964	−0·310	—

Duration of drought

Non-o'lapping Rank	18 months			24 months			30 months			36 months		
	Starting Date	$D_{m,1}$	O'lapping Rank	Starting Date	$D_{m,1}$	O'lapping Rank	Starting Date	$D_{m,1}$	O'lapping Rank	Starting Date	$D_{m,1}$	O'lapping Rank
1	Aug 1920	−0·376	1	Nov 1932	−0·308	1	Aug 1920	−0·272	1	Sep 1971	−0·237	1
2	Sep 1971	−0·350	4	Nov 1920	−0·304	2	Aug 1947	−0·265	2	Oct 1920	−0·228	3
3	Jun 1933	−0·336	7	Jun 1972	−0·285	7	Jul 1971	−0·260	3	Dec 1931	−0·223	5
4	Feb 1943	−0·327	10	Aug 1947	−0·277	12	Jun 1932	−0·249	5	Feb 1943	−0·221	6
5	Apr 1897	−0·319	17	Sep 1897	−0·267	16	Apr 1897	−0·236	15	Jul 1947	−0·202	13
6	Apr 1948	−0·278	39	Mar 1900	−0·251	27	Jun 1943	−0·224	24	May 1899	−0·198	18
7	Jan 1959	−0·262	—	Mar 1943	−0·239	36	Mar 1900	−0·180	—	Dec 1895	−0·156	—
8	Mar 1873	−0·257	—	Mar 1883	−0·166	—	Dec 1953	−0·175	—	Mar 1961	−0·131	—
9	Sep 1900	−0·253	—	Jul 1955	−0·165	—	Mar 1883	−0·137	—	Jun 1953	−0·129	—
10	Dec 1954	−0·251	—	Mar 1961	−0·149	—	Mar 1961	−0·128	—	Apr 1904	−0·109	—

A dash indicates that the overlapping rank exceeds 40.

TABLE III—'METEOROLOGICAL' DROUGHT AT KEW FROM 1871 TO 1975:

$$D_{m,s} = [(R - E_p) - (\bar{R} - \bar{E}_p)]/\bar{R}$$

Duration of drought

Non-o'lapping Rank	30 days Starting Date	30 days $D_{m,s}$	30 days O'lapping Rank	60 days Starting Date	60 days $D_{m,s}$	60 days O'lapping Rank	90 days Starting Date	90 days $D_{m,s}$	90 days O'lapping Rank	4 months Starting Date	4 months $D_{m,s}$	4 months O'lapping Rank
1	1 Jul 1921	−1·406	1	4 Jun 1921	−1·293	1	3 Jun 1975	−1·137	1	Jun 1959	−1·003	1
2	3 Jun 1975	−1·402	3	15 Mar 1893	−1·214	3	14 May 1921	−1·125	2	May 1921	−0·938	2
3	1 Sep 1959	−1·388	4	14 Aug 1959	−1·207	4	27 Apr 1959	−1·042	5	Aug 1947	−0·847	6
4	10 Apr 1942	−1·379	5	3 Jul 1899	−1·176	5	5 Aug 1947	−0·951	9	Mar 1957	−0·817	8
5	27 Jul 1899	−1·362	6	3 Jun 1975	−1·151	7	1 Jul 1899	−0·948	10	Mar 1893	−0·807	9
6	1 Apr 1893	−1·340	8	1 Jul 1911	−1·139	9	30 Jun 1911	−0·947	12	Jul 1972	−0·800	10
7	5 Aug 1947	−1·338	9	27 May 1959	−1·128	11	1 Feb 1938	−0·942	15	Mar 1938	−0·798	11
8	25 Jun 1911	−1·268	12	19 Jul 1947	−1·116	12	1 Apr 1957	−0·933	17	Jun 1949	−0·772	14
9	5 May 1919	−1·262	13	17 Jun 1887	−1·072	14	14 Mar 1893	−0·928	18	May 1975	−0·762	15
10	26 Jun 1959	−1·246	15	2 May 1895	−1·015	16	7 Aug 1972	−0·901	21	Feb 1956	−0·758	16

Duration of drought

Non-o'lapping Rank	5 months Starting Date	5 months $D_{m,s}$	5 months O'lapping Rank	6 months Starting Date	6 months $D_{m,s}$	6 months O'lapping Rank	9 months Starting Date	9 months $D_{m,s}$	9 months O'lapping Rank	12 months Starting Date	12 months $D_{m,s}$	12 months O'lapping Rank
1	May 1959	−0·995	1	May 1959	−0·877	1	Feb 1921	−0·717	1	Jan 1921	−0·599	1
2	Apr 1921	−0·849	3	Feb 1921	−0·810	3	Feb 1959	−0·700	2	Apr 1972	−0·557	5
3	Feb 1938	−0·819	5	Feb 1938	−0·736	8	Jul 1972	−0·595	10	May 1959	−0·506	9
4	Jun 1972	−0·738	8	May 1972	−0·711	9	Jun 1933	−0·534	18	Jul 1933	−0·490	13
5	Jul 1947	−0·734	9	Mar 1893	−0·644	13	Jan 1949	−0·510	21	Oct 1948	−0·409	38
6	Apr 1975	−0·676	14	Jul 1947	−0·628	15	Jan 1929	−0·496	23	Oct 1897	−0·406	39
7	Mar 1893	−0·669	15	Jul 1933	−0·575	20	Jan 1893	−0·476	27	Jul 1964	−0·393	—
8	Feb 1895	−0·643	20	Sep 1964	−0·568	21	Aug 1947	−0·464	29	Aug 1947	−0·379	—
9	May 1911	−0·625	21	Jan 1895	−0·566	22	Jul 1964	−0·446	32	Apr 1943	−0·374	—
10	May 1899	−0·615	23	Apr 1949	−0·565	23	Feb 1938	−0·444	34	Jul 1955	−0·373	—

Duration of drought

Non-o'lapping Rank	18 months Starting Date	18 months $D_{m,s}$	18 months O'lapping Rank	24 months Starting Date	24 months $D_{m,s}$	24 months O'lapping Rank	30 months Starting Date	30 months $D_{m,s}$	30 months O'lapping Rank	36 months Starting Date	36 months $D_{m,s}$	36 months O'lapping Rank
1	Jan 1921	−0·435	1	Jun 1972	−0·402	1	Dec 1971	−0·373	1	Sep 1971	−0·348	1
2	Jun 1933	−0·428	2	Nov 1932	−0·378	6	Apr 1947	−0·315	11	May 1899	−0·253	11
3	Jun 1972	−0·425	3	Dec 1920	−0·335	16	Jun 1932	−0·291	13	Nov 1932	−0·249	12
4	Jan 1959	−0·422	6	Aug 1947	−0·324	21	Aug 1920	−0·284	16	Jul 1947	−0·240	20
5	Mar 1943	−0·361	26	Oct 1897	−0·301	28	Apr 1897	−0·276	19	Oct 1920	−0·236	25
6	Apr 1897	−0·330	—	Mar 1900	−0·296	32	Mar 1943	−0·233	—	Feb 1943	−0·227	32
7	Apr 1948	−0·317	—	Mar 1943	−0·259	—	Feb 1959	−0·210	—	Mar 1961	−0·174	—
8	Jun 1900	−0·314	—	Oct 1958	−0·249	—	Jan 1963	−0·172	—	Dec 1895	−0·172	—
9	Dec 1954	−0·280	—	Jul 1955	−0·206	—	Jan 1955	−0·171	—	Nov 1956	−0·171	—
10	Apr 1928	−0·250	—	Mar 1961	−0·196	—	Mar 1883	−0·165	—	Apr 1904	−0·134	—

A dash indicates that the overlapping rank exceeds 40.

When E_p is taken into account it falls to third in the rankings. The period from February to April is described by Brooks (1938). If this period of dry weather had occured wholly in either the summer or the winter it would certainly have produced either a severe 'grassland' or 'hydrological' drought. In the event, however, there was no 'hydrological' drought and 'grassland' effects were only moderate, the early summer of 1938 giving the seventh worst 'grassland' drought.

1947

The dry weather of August 1947, described by Glasspoole and Rowsell (1950), marked the start of the third most severe rainfall deficiency to be recorded over a period of four months. Then, after a respite throughout much of 1948, the 12 months starting in October of that year were the sixth driest in over 100 years. The close proximity of these two dry spells meant that the 30 month period starting in April 1947 ranks as the second driest 30 month period to be recorded. The summer of 1949 gave the sixth worst 'grassland' drought while maximum 'hydrological' severity was attained over a period of two years, when the winters of 1947–48 and 1948–49 gave the fourth lowest total of R_e.

1959

The dry weather during the summer of 1959, described by Bleasdale and Grindley (1959), extended from May to September. The rainfall deficiency ranks fifth over a period of five months, but when the effects of E_p are included it rises to first place. The accompanying 'grassland' drought stands as the worst on record.

TABLE IV—'HYDROLOGICAL' DROUGHT AT KEW FROM 1871 TO 1975

	1 year		2 years		3 years	
Rank	Year	R_e(mm)	Year	R_e(mm)	Year	R_e(mm)
1	1890	0·0	1972	55·7	1971	147·7
2	1933	0·0	1933	73·5	1962	184·4
3	1964	0·0	1971	92·0	1919	202·8
4	1972	0·0	1947	98·8	1932	231·6
5	1897	7·8	1900	106·2	1943	233·0
6	1943	34·5	1889	112·5	1970	235·3
7	1901	38·4	1963	115·2	1920	248·0
8	1873	45·8	1920	138·0	1947	260·3
9	1908	45·8	1919	149·6	1931	267·5
10	1947	49·2	1897	150·1	1953	281·4
Mean		158·1		316·2		474·3

TABLE V—'GRASSLAND' DROUGHT AT KEW FROM 1871 TO 1975

Rank	Year	$E_p - E_g$
1	1959	344·5
2	1921	320·7
3	1893	290·9
4	1972	285·0
5	1975	277·8
6	1949	271·2
7	1911	264·2
8	1938	258·4
9	1899	258·2
10	1933	241·4
Mean		142·2

1964

Smith (1965) draws attention to an interesting example of 'hydrological' drought which took place between the years of 1962 and 1965. The overall rainfall deficiency at Kew during this period was quite unexceptional and the period barely enters the ranking for 'meteorological' drought. Such rainfall deficiency as there was, however, occurred mainly during the winter months and a surprisingly severe 'hydrological' drought ensued. No R_e occurred during the winter of 1964–65 and, taken with the two previous winters, this led to the second worst example of 'hydrological' drought over three years.

TABLE VI—RANKING OF SELECTED DROUGHTS AT KEW FROM 1871 TO 1975

	Duration	1890	1893	1898	1921	1933	1947	1959	1964	1972
	30 days	—	—	—	5	—	—	3	—	—
	60 days	—	2	—	1	—	9	6	—	10
	90 days	—	—	—	2	9	3	—	—	7
	4 months	—	10	—	1	7	3	9	—	6
	5 months	9	—	—	2	6	4	5	—	3
$D_{m,1}$	6 months	5	—	—	2	—	8	7	—	3
	9 months	4	—	—	1	3	—	5	—	2
	12 months	—	—	3	1	4	—	9	—	2
	18 months	—	—	5	1	3	—	7	—	2
	24 months	—	—	5	2	1	4	—	—	3
	30 months	—	—	5	1	4	2	—	10	3
	36 months	—	—	5	2	3	5	—	8	1
	30 days	—	6	—	1	—	7	3	—	—
	60 days	—	2	—	1	—	8	3	—	—
	90 days	—	9	—	2	—	4	3	—	10
	4 months	—	5	—	2	—	3	1	—	6
	5 months	—	7	—	2	—	5	1	—	4
$D_{m,2}$	6 months	—	5	—	2	7	6	1	8	4
	9 months	—	7	—	1	4	8	2	9	3
	12 months	—	—	6	1	4	8	3	7	2
	18 months	—	—	6	1	2	—	4	—	3
	24 months	—	—	5	3	2	4	8	10	1
	30 months	—	—	5	4	3	2	7	8	1
	36 months	—	—	2	5	3	4	—	7	1
	1 year	0	—	5	—	0	10	—	0	0
D_h	2 years	6	—	10	8	2	4	—	7	1
	3 years	—	—	—	3	4	8	—	2	1
D_a	1 year	—	3	—	2	10	—	1	—	4

$D_{m,1}$ represents 'meteorological' drought based on rainfall; $D_{m,2}$ represents 'meteorological' drought based on $(R - E_p)$; D_h represents 'hydrological drought' and D_a represents 'grassland' drought.
A dash indicates that the drought is not one of the ten most severe recorded in the period.
An entry of zero for D_h indicates one of several observations of zero R_e.

1972

The long period of dry weather centred on the years of 1972 and 1973 was recently pointed out by Jerome (1975). Over a period of 36 months the rainfall deficiency stands as the worst on record, and when E_p is taken into account its severity increases, first position then being occupied for durations of from 24 to 36 months. The 'grassland' drought of 1972 was the fourth most severe on record, but the 'hydrological' effects are outstanding. The winter of 1972–73 was one of four which failed to record any R_e, and the low totals of R_e observed during the preceding and succeeding winters ensured that the 'hydrological' drought over two and three years was the worst ever recorded.

1976

Since the above account was written an outstanding drought has taken place which it has not been possible to include in the full calculations, but a few comments are made here. The winter of 1975–76 was unranked in terms of 'hydrological' drought, but the rainfall deficiency for periods ending in August 1976 occupied first position for durations of from seven to eleven months, and again for fifteen months. Over the nine months starting in December 1975, rainfall was only 35·5 per cent of average. Calculations of 'grassland' drought have not been made, but the summer of 1976 is likely to compare with those of 1959 and 1921.

ACKNOWLEDGEMENTS

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SATELLITE INFRA-RED NEPHANALYSES

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SUMMARY

Although infra-red imagery has been available to the meteorological user community around the world for several years via direct read-out from American weather satellites, there is no accepted international scheme for nephanalyses based on such data. This paper explores the more obvious possibilities for formal schemes of infra-red nephanalysis, and presents examples of the application of four such schemes by the analyst to a selected infra-red image. The operational user is thereby offered a choice of method for incorporation into his particular program.

INTRODUCTION

The availability of visible imagery from meteorological satellites to the local user has long been appreciated by the weather-forecasting community. Detailed schemes for the identification of clouds in satellite pictures appeared soon after the first weather satellite was launched in 1960 (Conover, 1962, 1963), and comprehensive manuals for the interpretation of clouds and cloud organizations were available in the mid 1960s (e.g. WMO, 1966). From an early stage in the development of weather-satellite systems designed to give an adequate coverage of middle and high latitudes (following the pioneer satellites whose coverage was mainly tropical), forecasters wrote enthusiastically of the increased accuracy in short-term forecasting which was possible when the new data were consulted (e.g. Houghton, 1965). However, some means had to be devised whereby relevant information could be extracted from the satellite pictures for presentation to the duty forecaster for evaluation alongside the conventional weather observations. Thus the satellite nephanalysis was conceived. Until recently, this remained the only satellite-derived statement to be invoked during the operational forecasting procedure. Whilst new possibilities have opened up recently for the provision of numerical data from satellites to be used in computer-based forecasting procedures in principal meteorological offices (for example, vertical profile data from sounding spectrometers (Atkins and Jones, 1975)), hand-drawn cloud and weather-system analyses have by no means outlived their usefulness, especially for regions where upwind weather observations are sparse, or for some reason numerical forecasting is inadequate or inappropriate. It was for this reason that the present authors proposed recently an improved scheme for the nephanalysis of satellite visible images, updating and extending the scheme which has been in widespread use for more than a decade (Harris and Barrett, 1975).

We now consider satellite infra-red images, whose availability is as regular and easy as that of the visible images, but whose contents have been utilized less in forecasting operations, especially in developing countries. Although the physical implications of the infra-red cloud images are less complex than those of the visible images, the day-to-day use of infra-red imagery has often been of a decidedly *ad hoc* nature.

Regular usage of infra-red imagery is desirable on three operational grounds in particular, namely:

(a) as supplementary information on cloudiness for those situations for which visible imagery is also available,

(b) as additional information on cloudiness for those regions not served by geostationary satellites, doubling the opportunity for viewing cloud fields (by providing information on night-time as well as day-time conditions), and

(c) as the only available information on cloudiness for high-latitude regions when under the influence of winter darkness.

THE CHARACTERISTICS OF INFRA-RED IMAGERY

Although from an early stage in the development of operational infra-red radiometers efforts have been made to extract useful information therefrom (e.g. Boldirev, 1968; Koffler *et alli*, 1973) some potential users seem to have recognized only that visible and infra-red images often indicate different attributes of clouds without seeking to enquire seriously why and how they differ, or, conversely, to what extent their contents may be similar.

The most significant feature of infra-red cloud information is that the radiation temperature of the cloud is a function of the cloud-top altitude. Problems arise where radiation from below becomes compounded with radiation from the cloud itself, for example, in thin sheets of cirrus or cirrostratus (e.g. Fritz and Rao, 1967), and where cloud elements, or breaks in a cloud field, fall below the resolution of the imaging system, for example, where fair-weather cumuli or stratocumuliform sheets are found. However, the three-dimensional view which the infra-red approach affords is immediately striking and its advantages are clear when contemporaneous visible and infra-red images of equal resolution are compared, for example, in the correct identification of jet-stream cirrus (Valovcin, 1968).

Unfortunately, the resolution of early infra-red sensors—including the so-called High Resolution Infra-red Radiometer (HRIR) flown initially on NIMBUS 2 in 1964—was rather coarse for detailed differentiation of cloud types and cloud-field analysis (see Barrett, 1974). However, current sensors—notably the Very High Resolution Radiometer (VHRR) on NOAA satellites (0·9 km*), and the high-resolution scanning radiometers on DMSP (Defense Meteorological Satellite Program) satellites (0·6 km) (Air Weather Service, 1974), provide first-class data which have much reduced the problems related to cloud or cloud-break size versus the resolving power of the satellite system. Currently, there are few if any cloud varieties which may be positively identified on a visible image but not on a contemporaneous infra-red image of the same resolution.

Concerning similarities between the two image types, the existing literature is very sparse. However, it is worth noting that similarities do exist, particularly in the apparent areal extent of cloud. Although differences may be apparent in the internal structures of clouds and cloud fields, their outlines are almost always much the same in the two types of imagery. Of course, where thin cloud exists, whether high or low, slight variations may occur depending on the relationships between cloud and background brightness in the visible waveband, or cloud and Earth surface temperatures in the infra-red, but close outline correspondence is the rule rather than the exception.

Our studies further indicate that most of, if not all, the features of cloud structure apparent in visible images may be identified on infra-red images also. Since the infra-red systems provide data with more direct physical meaning and

* All resolution statistics represent sub-satellite point performances.

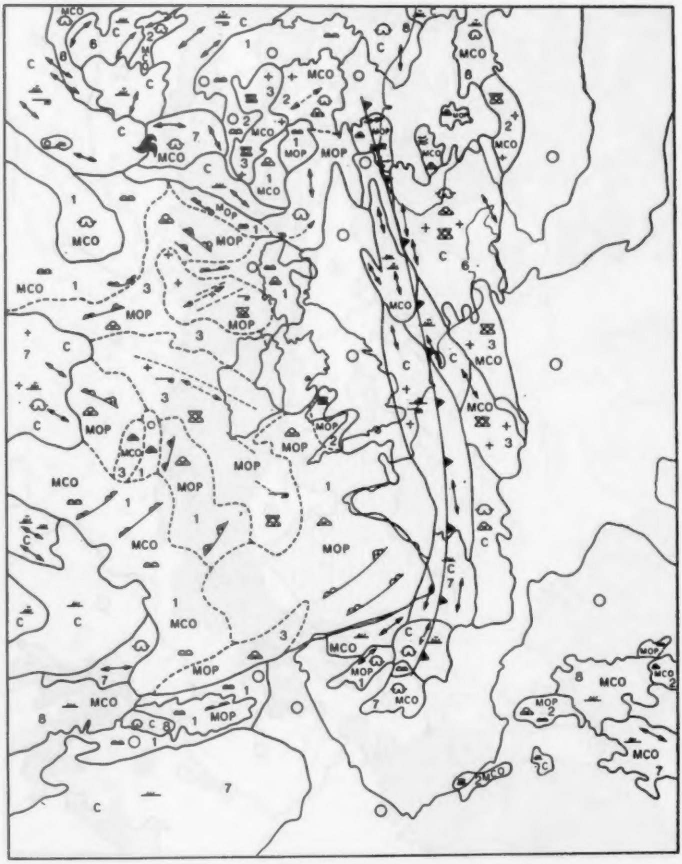

FIGURE 1—CONVENTIONAL NEPHANALYSIS OF THE DMSP INFRA-RED IMAGE SHOWN IN PLATE I

improve our view of the weather in various regions and different circumstances, as indicated on p. 11, we believe that proposals designed to formalize their analysis, and therefore to standardize the products prepared by different analysts to a greater extent, should lead to clear benefits for both operational and subsequent research users of infra-red data.

THE CHOICE OF AN INFRA-RED NEPHANALYSIS PROCEDURE

A number of possible schemes for infra-red nephanalysis may be readily envisaged. These include:

(a) A scheme employing the long-standing and internationally accepted (visible) nephanalysis code of symbols.

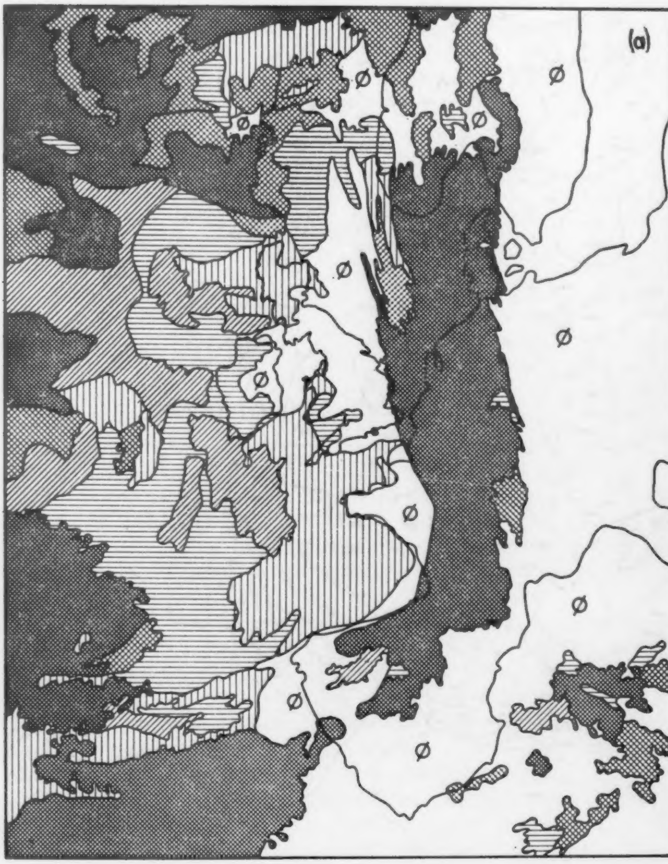

FIGURE 2—NEPHANALYSIS FOLLOWING THE IMPROVED (VISIBLE) SCHEME SUGGESTED BY HARRIS AND BARRETT (1975)

(a) cloud amount (b) cloud type and structure
(c) interpretation (d) key for Figures 2(a)–(c)

(b) A scheme following the procedure for improved operational nephanalysis of visible images, as outlined by Harris and Barrett (1975).

(c) A new scheme designed to recognize and, on a single map, to represent the special characteristics of infra-red images.

(d) A more detailed scheme for infra-red imagery analysis with the significant information displayed in a group of content-specific maps. This may be viewed as the infra-red counterpart to the improved (visible) nephanalysis (see (b) above). The sum of the parts would present considerably more information than the single-map infra-red nephanalysis.

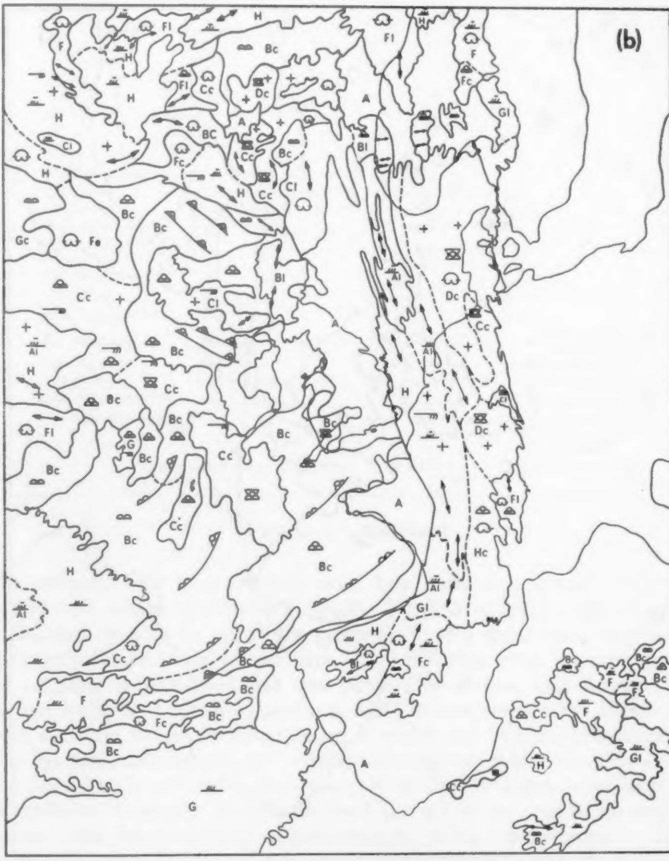

FIGURE 2—*continued*

The rationale behind this suggestion of a range of possibilities is two-fold. First, different users may have different needs, and, second, some users may wish to standardize their visible and infra-red nephanalyses on comparable bases, whilst others may have more opportunity for experiment. In every case, however, we feel that the objectives for satellite nephanalysis recognized and listed by Harris and Barrett (1975, p. 11) should be borne in mind, especially those necessitating an appropriate scale filter and standardization of the satellite image interpretation procedure.

THE PROPOSED ALTERNATIVES

We may profitably pass some further comments upon each of the procedures listed above in turn, with particular reference to the worked examples presented here as Figures 1–4, all of which are based on the same satellite image (Plate I).

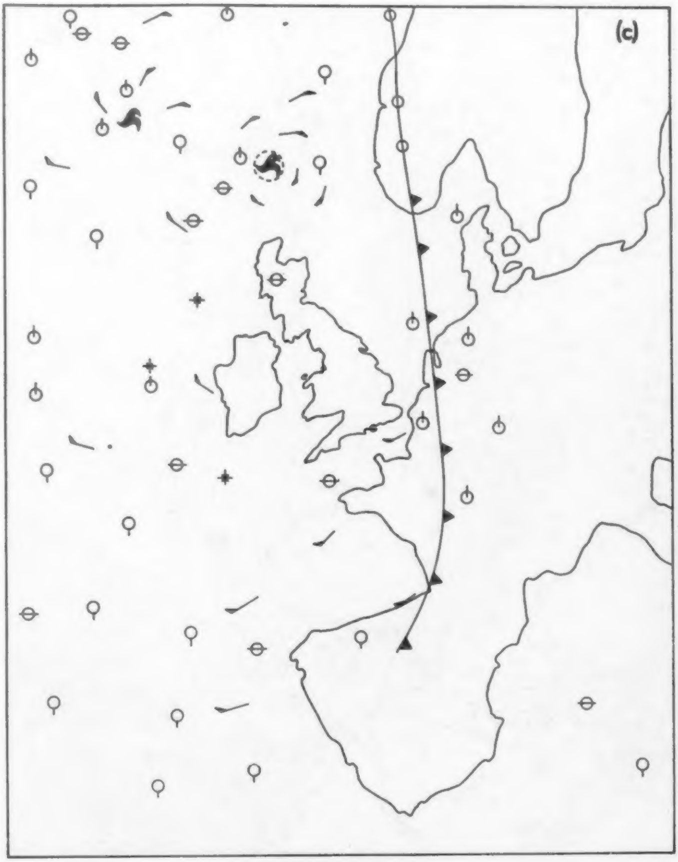

FIGURE 2—*continued*

(a) Figure 1 demonstrates that, when the differences in image characteristics are borne in mind, it is perfectly possible to produce infra-red nephanalyses directly comparable to the standard visible nephanalyses. No further comments are necessary in this case.

(b) The 'improved' nephanalysis portrayed by Figure 2 contains more detail than the standard, single-map format. It distinguishes between three basic aspects of cloudiness, namely cloud amount, cloud type and structure, and the interpretation of cloud features. Such maps may be best presented, side by side, the cloud-cover map serving as the central one of the three, with the other two as flanking overlays. In this way, any two, or all three, may be examined together as the need arises.

(c) More detailed comments are required in the case of this newly designed format. Here, special attention is paid to those aspects of infra-red imagery which are most characteristic and distinctive, namely 'cloud brightness' and

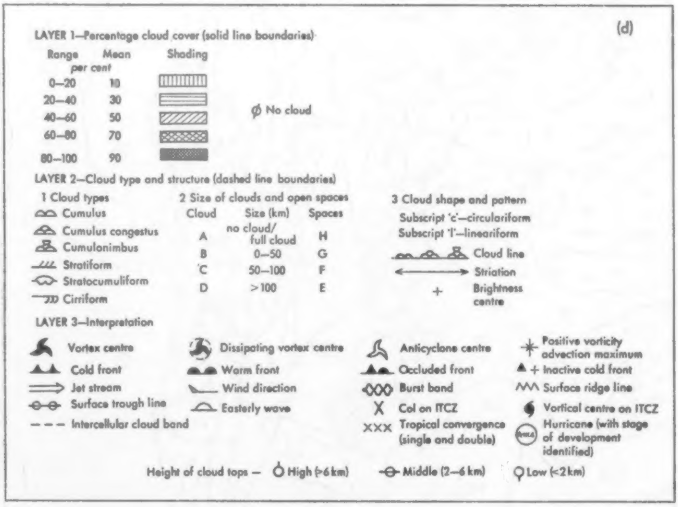

FIGURE 2—*continued*

'cloud texture'. We have already seen how infra-red picture brightness is generally well related to cloud-top height. Three brightness categories may be differentiated speedily by eye in the preparation of a single-panel nephanalysis, namely very bright, bright, and dim. The resulting map is interpretable in terms of high, middle-level and low cloud (see Bittner and Ruggles, 1970). Although synoptic, latitudinal and seasonal factors preclude the assignment of precise, constant values to the altitudes at which one brightness category gives way to the next, this fast 'eyeball' method of cloud-level identification involving so few categories is sufficiently accurate to be invoked in hand-drawn nephanalysis procedures, especially if the latitudinal spread of the area of interest is not excessive. For future uses of satellite-derived cloud-top information in computer-based forecasting programs, it will be necessary to take both local and zonal variations in temperature–height relationships into account.

Of course, it should not be forgotten that background (terrestrial) features are easily ignored by a human analyst: this is one of the most important ways in which 'eyeball' analyses score over machine-based (objective) methods of analysis currently under development. It should be noted further that, in our example, the brightness classes relate to the dominant brightness levels in each area: these would be much more difficult to assess by eye. The second most striking characteristic of the cloud contents of infra-red imagery is the 'texture' of the clouds. The key to Figure 3 illustrates the simple dendrogram on which its texture content is based.

Although Conover (1962) suggested that six criteria are necessary for successful cloud identification, namely cloud element size, shape, organization and shadow effects, in addition to brightness and texture, we feel that for most purposes the last two, considered carefully, are usually sufficient, especially in the case of infra-red studies where brightness indicates for most cloud types

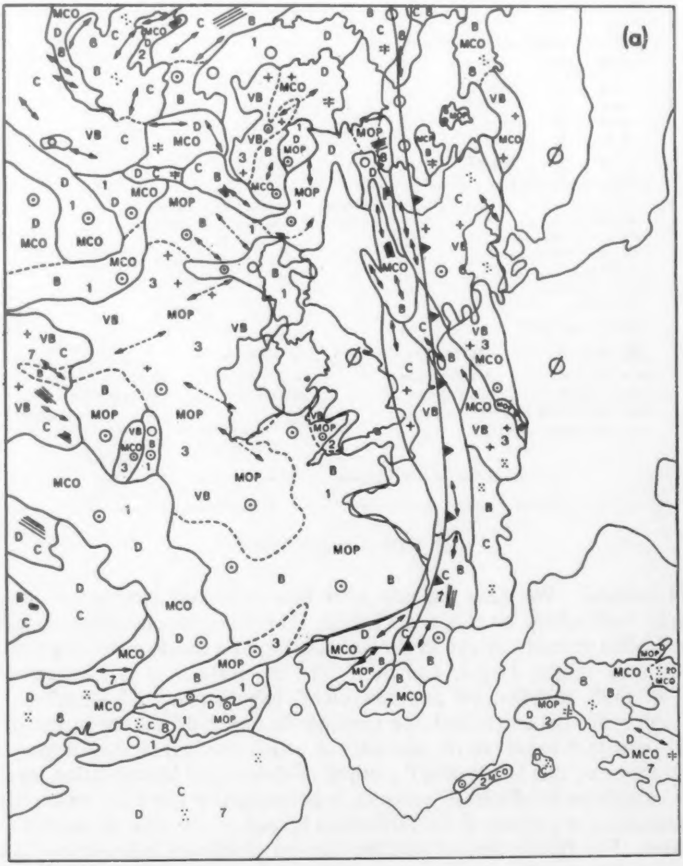

FIGURE 3(a)—SINGLE-PANEL INFRA-RED NEPHANALYSIS DISPLAYING CLOUD AMOUNT, BRIGHTNESS, TEXTURE AND INTERPRETATION FEATURES

the height of the cloud tops. The other types of information in Figure 3, the single-panel infra-red nephanalysis, are the familiar but invaluable categories of cloud amount (as in (a) in case the two might be used together), and feature interpretation. The whole has been designed to give about the same density of information content as (a), assuming the same minimum size thresholds of about 1° square for areal features and 2° long for linear features.

(d) The infra-red nephanalysis represented by Figure 4 is the most detailed that we feel might be required for either operational or research applications. The same minimum size thresholds are employed as in (c), but the various information categories are all enhanced to give more classes of subdivision. For example, the cloud-amount categories are now six instead of four, there are six cloud-brightness categories instead of three, and nine texture classes instead

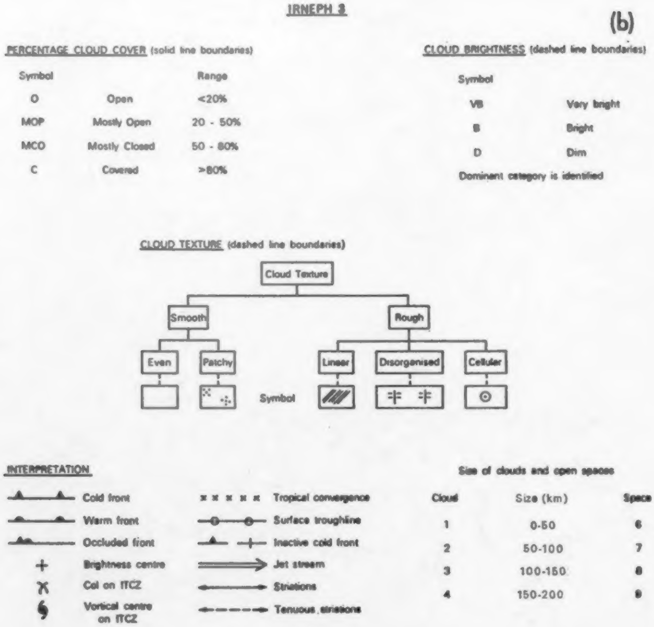

FIGURE 3(b)—KEY FOR FIGURE 3(a)

of five. The detailed additions may be identified by comparing the keys for Figures 2 and 4. Four panels or layers have been constructed for Figure 4, rather than the three in its visible counterpart (Figure 2) because we feel that the newness of the approach necessitates the extra flexibility for intercomparison between the types of information represented. It would be possible, with no loss of detail or any danger of overloading, to combine the cloud-amount and cloud-brightness panels should the saving in space be preferred. The brightness classes are based on the three utilized in the single-panel neph-analysis with three new classes added to indicate areas of roughly equal brightness mixtures. The shading relating to the nine texture classes is generally non-directional, though directional indications can be given where linear features are concerned.

CONCLUSIONS

There seem to be no irresistible reasons why infra-red images from weather satellites should not be invoked more widely as important contributors to the total information pool for short-term forecasting and allied research. One brake to progress hitherto seems to have been the lack of confidence of some people to analyse such images effectively. This paper has demonstrated that there are at least three broad choices available to would-be users of these valuable synoptic data, namely:

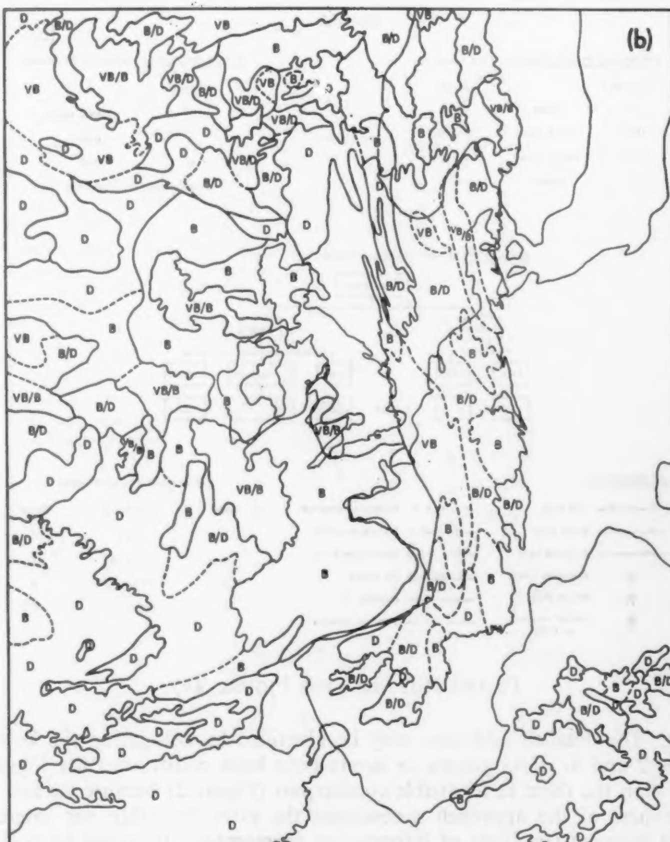

FIGURE 4—DETAILED FOUR-LEVEL NEPHANALYSIS

(a) cloud amount (see Figure 2(a)) (b) infra-red cloud brightness
(c) cloud texture (d) interpretation (e) key for Figures 4(a)–(d)

(a) Existing schemes of nephanalysis may be applied to the infra-red images in conjunction with the simultaneous visible images, to produce single nephanalyses from the combined evidences of the two different data types. For general purposes this might be the preferred course of action.

(b) Existing schemes of nephanalysis may be applied separately to infra-red data, perhaps for purposes of comparison with independently drawn visible nephanalyses. Perhaps such infra-red charts might be prepared most profitably for illustrating visible data-remote situations or for specialized applications or both, e.g. upper tropospheric forecasting for aviation.

(c) The analyst may apply purpose-built schemes to identify and represent

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PLATE I—INFRA-RED IMAGE FROM AMERICAN DEFENSE METEOROLOGICAL SATELLITE PROGRAM (DMSP) SATELLITE S, 0125 GMT, 30 APRIL 1975

The nominal best resolution of the scanning radiometer responsible for this image is about 0·6 km.
(See page 15.)

PLATE II—THE METEOROLOGICAL OFFICE TRANSMISSOMETER

This photograph was taken looking east along the main compound on the north side of the M4 motorway near Theale in Berkshire. The transmitter unit of the Transmissometer is in the foreground, with the meteorological sensors and other visibility instruments at the mid point of the compound. This experiment was part of a co-operative trial also involving the Home Office and the Transport and Road Research Laboratory.

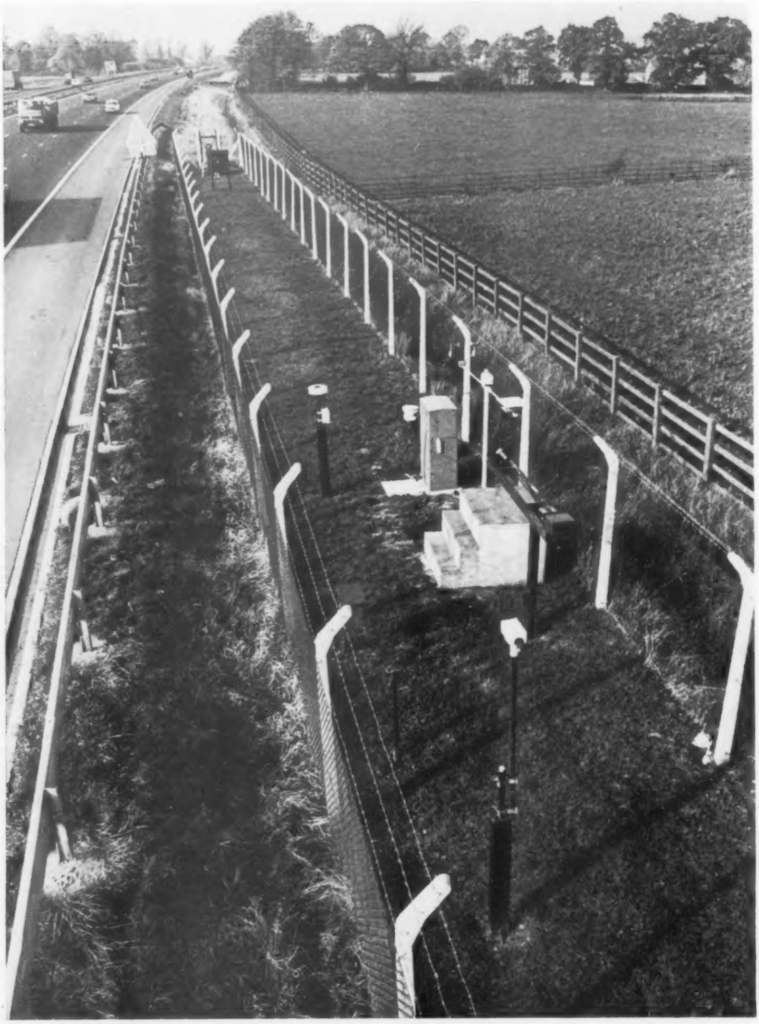

PLATE III—THE METEOROLOGICAL OFFICE TRANSMISSOMETER

This photograph was taken looking west along part of the main compound beside the M4 motorway near Theale. In the foreground are the visibility instruments undergoing comparison, and the meteorological sensors, with a background light meter in the near foreground. At the far end of the compound is the transmitter unit of the Transmissometer, which was the instrument standard during this co-operative trial involving the Transport and Road Research Laboratory and the Home Office.

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PLATE IV—THE METEOROLOGICAL OFFICE COLLEGE AT SHINFIELD PARK

Rear view of the Lodge

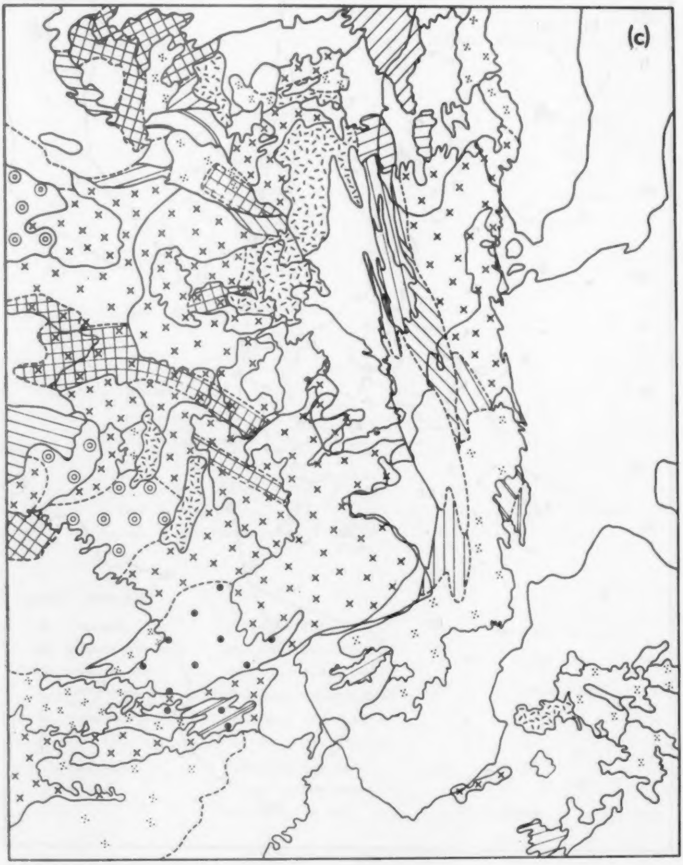

FIGURE 4—*continued*

not only the traditionally recognized features of satellite cloud images, but also certain other image variables (especially brightness and texture) whose implications have been rather neglected hitherto.

Looking further into the future, we would expect 'objective', machine-effected methods of picture analysis to become increasingly prevalent. TIROS N, the likely configuration for the polar-orbiting operational satellites of the early 1980s, will provide directly (through its on-board digitization of visible and infra-red images) the numerical data required as the input to such a program. For this, a new approach may be required to the description and classification of clouds; an appreciation of new aspects of cloudiness and its relations with other atmospheric parameters may be the prize for success.

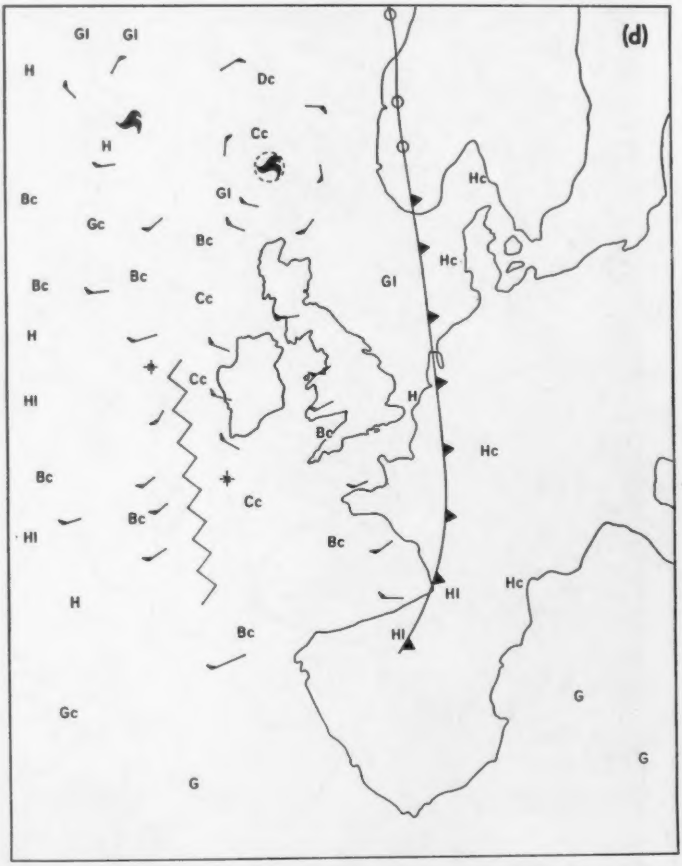

FIGURE 4—*continued*

In image science, it is generally accepted that objective analyses based on more characteristics are usually more successful than others based on fewer. Clearly the special characteristics of infra-red images are likely to be just as important in the search for objective schemes of nephanalysis as those with which we have become so familiar in visible cloud imagery.

For the immediate future it may be necessary for us to analyse infra-red images straightforwardly in terms of picture brightness and texture, as we have done here, rather than to attempt probably unsatisfactory interpretations of combinations of these qualities in terms of conventional cloud classes with little regard for detailed features. The greatest advantage of this scientific honesty might eventually emerge from the consequent opportunity to examine cloudiness in a new light, cut free from the constraints of the rather subjective and often clumsy standard scheme of cloud classification. For the immediate future, we foresee no insuperable problems for the meteorologist who might

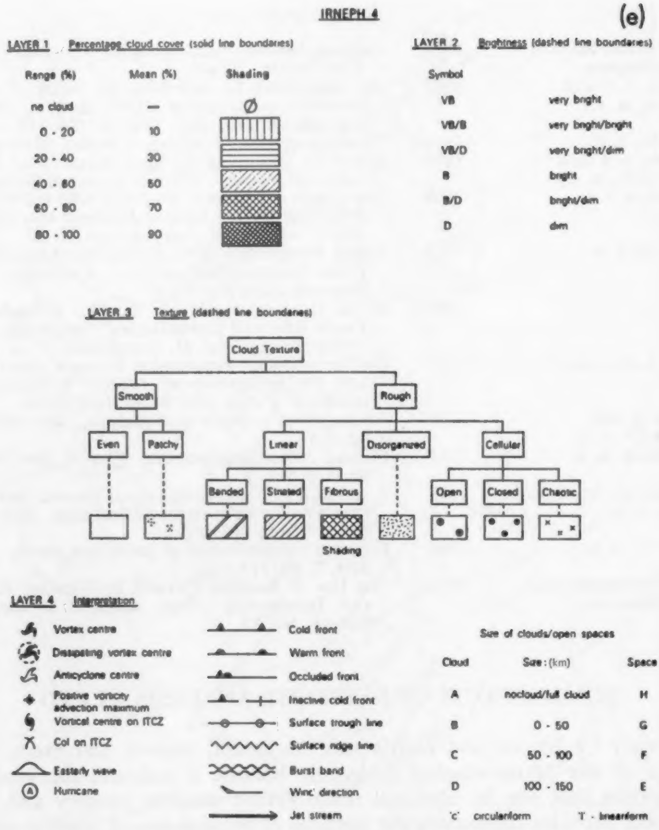

FIGURE 4—*continued*

choose to use our proposals for purpose-built infra-red nephanalyses alongside the rather different visible products: there are readily recognizable affinities between, for example, a cold front composed of a thick mixture of stratiform and cumulonimous cloud and a belt of very bright, rough-textured cloud in middle latitudes.

Finally, a word about the operational practicabilities of the schemes outlined in this paper. We have convinced ourselves that, after a suitable period of training, it would be possible for an analyst to prepare nephanalyses of any of the types introduced above within one hour, which we have taken to be the maximum acceptable time to elapse between receipt of the satellite signal and the transference of the analysed image to the prognostics section. Our research into cheap, efficient ways of undertaking comparable analyses as far as possible by objective means is continuing, and we hope to present some findings and suggestions soon.

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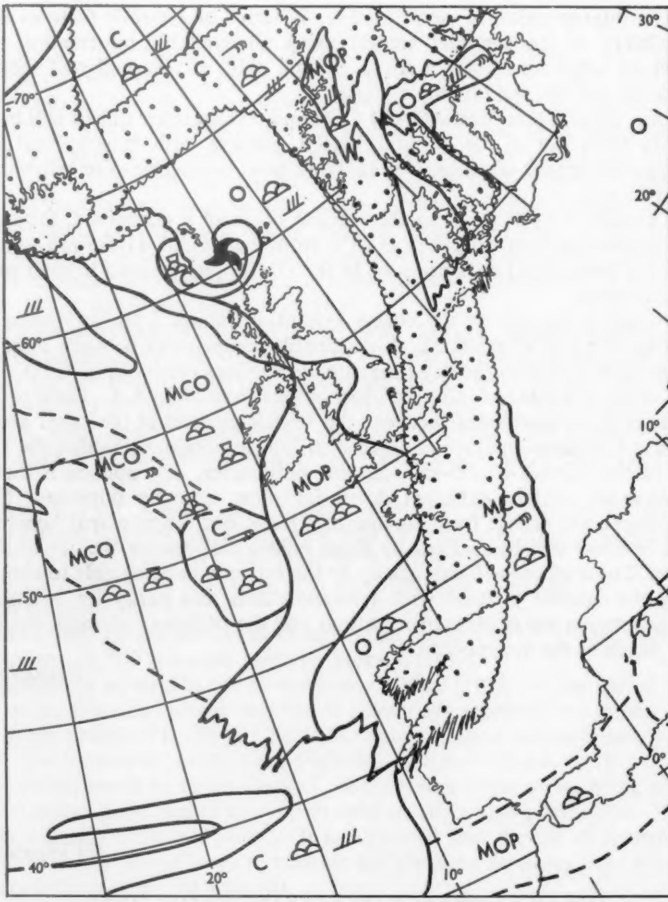
SOME ASPECTS OF SATELLITE ANALYSIS AT CFO

The paper by Barrett and Harris will, no doubt, interest and excite many readers of the *Meteorological Magazine* because it indicates the wealth of information that can be obtained from VHRR satellite imagery and, also, because it provides suggestions for methods of presentation of satellite pictures by a central office to those stations unable to receive the data directly.

Although CFO does not currently receive VHRR pictures these will be available in the near future. When such data are available the area received will be less than that on the DMSP picture used by Barrett and Harris because of the time taken firstly to process the VHRR signal at the receiving station and then to transmit the picture to Bracknell. The British Isles, North Sea and English Channel will normally be covered as routine with, in addition, one other similar-sized area available on request depending upon the weather situation. Routine satellite work in CFO will, in the immediate future, continue to be based upon the comparatively low-resolution imagery (2·5 km in the visual spectrum and 5 km in the infra-red) obtained from polar orbiting satellites (such as NOAA 4) and geostationary satellites (such as SMS 1 and the projected METEOSAT) enhanced by VHRR pictures in the vicinity of the British Isles.

My personal opinion regarding the analysis systems proposed by Barrett and Harris is that the techniques, although interesting and useful in investigation or research work, would be impracticable or, at best, of limited value in an operational environment. Reasons for this opinion are as follows:



OPERATIONAL IR NEPHANALYSIS PRODUCED AT CFO ON THE EVENING OF 29 APRIL 1975

(a) The size of some of the features portrayed is such that their life-times will only be an hour or so and, by the time analyses have been completed and broadcast, the features may well have ceased to exist.

(b) The complexity of the analyses in the paper by Barrett and Harris is such that, after dissemination by facsimile, much of the detail would be difficult to discern.

(c) Even if discernible, the quantity of detail on the analyses would not permit rapid assimilation and application by busy outstation forecasters.

(d) Some of the detail in the analysis is a matter of personal opinion. CFO analysts would, rightly or wrongly, take a different view of some of the features portrayed.

(e) The interpretation of cloud pictures in terms of synoptic features is the responsibility of the synoptic analyst using all available information. The decision on what constitutes a front, trough, ridge etc. should rest with the synoptician and not the satellite analyst.

It is my opinion that forecasters at CFO and certain other offices will benefit primarily from use of the original VHRR pictures with geographical grids superimposed instead of waiting for analyses, however ingenious or informative, to be produced.

As a comparison, in so far as the amount of detail is concerned, the operational satellite analysis produced in CFO from the NOAA 4 infra-red scanning radiometer about five hours previous to the DMSP picture used in their paper, is shown below.

The detail is limited by the coarse resolution (about 5 km as opposed to 0·5 km for the DMSP satellite). A reasonable compromise between these two extremes is provided by the day-time satellite analyses produced by CFO which are based upon visible and infra-red observations from NOAA 4. These provide a degree of detail somewhere between the VHRR pictures of the paper and the rather too simplistic analyses of cloud distribution obtainable within the limitations of the NOAA 4 infra-red scanning radiometer. My opinion is that the CFO analyses contain sufficient detail for most synoptic purposes. Some improvement will accrue from the use of VHRR but the principal benefits of VHRR imagery will be realized by those offices that receive the actual cloud pictures. These offices will gain partly by the forecasters being able to compare directly the satellite pictures with synoptic charts and partly by minimizing the time between the satellite observations and the pictures becoming available on the bench to the synoptician.

F. SINGLETON

551.578.42(41–4)

THE OCCURRENCE OF FALLING SNOW OVER THE UNITED KINGDOM

By M. C. JACKSON

Summary

The paper presents a variety of statistics on falling snow, mostly appropriate to the 1941–70 snow climatology. The statistics are especially useful to civil and municipal engineers and others concerned with the frequencies of falling snow, and of general interest to meteorologists, climatologists and geographers.

Values of the average annual number of days with falling sleet or snow are reduced to a common altitude of 100 m by an altitude adjustment factor. From these values a fairly smooth, small-scale map is drawn. A simple model is developed so that an objective estimate can be made of the number of days per winter with snow that is exceeded on average once in *n* years.

A method is described of estimating the number of hours of moderate or heavy falling snow in a winter. Some statistics are presented of the frequencies of snow accumulation rates in specified durations. The paper concludes with some details of associated weather conditions, and the probability of falling snow with the time of year.

1. Introduction

It is difficult to determine precisely the average number of days with sleet or snow falling. One reason for this is the difficulty of keeping a fully alert watch for the isolated snowflake or the isolated melting snowflake in a fall of sleet, particularly during the night. However, Manley (1958) published values of the average annual number of days with snow falling for the period 1926–55, by making a thorough intercomparison of records from different places and assessing the quality of each station record. Manley (1969) also made estimates of the number of days with falling snow in London in each of the last 300 winters. This record contains large apparent variations in the number of days in different eras, with especially small numbers between 1901 and 1940, and generally larger numbers before 1820.

The average number of snow days (days with sleet or snow falling at some time in the 24 hours) at Kew for the years 1912–38 was 14 days (Manley, 1958), but for the period 1941–70 the value increased to 19 days. In the last century Greenwich had 22 days for the period 1871–1900, and 17 days for the period 1841–70, when Sunday observations seemed suspiciously low (Manley, 1969). An average of 18 days was estimated for Camden Square for the period 1875–1900.

The winters with notably large numbers of snow days in London in the period 1841–1970 are (for this century at Kew, and for the last century at Greenwich):

1963 (54 days), 1917 (41), 1947 (39), 1955 (38);
1879 (54), 1888 (53), 1876 (36), 1891 and 1865 (35), 1870 and 1886 (34) and 1895 (33).

Further details of the snowiness of individual winters in the United Kingdom during the past 100 years are given by Jackson (1977).

Examination of data in the Meterological Office (1923) for the period 1881–1915 shows that the average number of snow days reported was mostly lower than in the period 1941–70 (see Table I). Many of these increases may well be simply due to a more constant and vigilant watch now than in the last century, which would result in fewer cases of sleet or very slight snow being missed. Snow statistics presented in this report refer mostly to the period 1941–70, and mostly use data from this period. It is suggested that the use of figures from this more recent period is more realistic for planning purposes than those for the very un-snowy period 1901–40.

Table I—Average number of days with snow falling

Location	Period 1881–1915	Period 1941–70
Scilly Isles	3	4
Falmouth	5	6
Dungeness	12	17
Kew Observatory	13	19
Oxford	17	25
Great Yarmouth	17	23
Holyhead	7	4
Stonyhurst College	26	25
Glasgow	17	31
Stornoway	25	35
Aberdeen	34	37
Wick	25	47
Braemar	47	71
Buxton	38	38

Although most of the data available for analysis were the number of days with snow falling, civil and municipal engineers are usually more interested in the duration of falling snow, and the total number of hours of falling snow. Later sections show how the latter results were derived, despite the shortage of direct data.

2. Mapping the 1941–70 mean annual number of days with sleet or snow falling

Climatological Memorandum No. 74 (Meteorological Office, 1975a) presents a map of the distribution of the mean annual number of days with snow falling in the period 1941–70, with further maps for each of the months November to April. The isopleths on all the maps are highly smoothed, but nevertheless reveal the very important role of altitude in the occurrence of falling snow shown previously by Manley (1940). A more detailed annual map was drawn for the present work using, in addition, values from 25 high-quality stations manned 24 hours a day by staff of the Meteorological Office, but not covering the whole 30 year period.

Manley (1940) produced a map of the mean annual number of days with snow falling for the period 1912–38, and recognized the very important role played by altitude. He calculated an average rate of increase with altitude (1 day for every 50 feet of altitude), and used this altitude correction figure to reduce the values for all stations above 200 ft to an equivalent altitude of 200 ft. These common-altitude values he then mapped. The major variation in these common-altitude values is with distance from the extreme south-west of England, while particularly large values are found at places exposed to the north-east, and particularly small values at places sheltered from the north-east.

A similar exercise was carried out with the 1941–70 data, and the increase in the mean annual number of snow days with altitude was calculated for a variety of regions. Data were often scanty, but the increase in the number of snow days with altitude seemed to vary over England and Wales between about 5·1 days per 100 m over Cornwall and Devon to 7·3 days per 100 m over North Wales. The largest value obtained was 11·4 days per 100 m over the Grampian region of Scotland. Values given in Climatological Memorandum No. 74 are 5 days per 100 m over Wales and the Midlands, and 8 days per 100 m over northern England.

For simplicity in the mapping, it seemed reasonable to adopt the single average value of 6·5 days per 100 m (1 day per 50 ft), first used by Manley (1940). This altitude correction was applied to the mean annual number of snow days at all stations to bring them to a common altitude. The common altitude chosen was 100 m, and the resultant values are mapped in Figure 1.

A pattern similar to that in Manley's paper is revealed, with values increasing away from extreme south-west England, and being especially high in regions exposed to the north-east. The 1941–70 values are in general significantly larger, but partly because the altitude of 100 m is greater than the 200 ft chosen by Manley; the difference in altitude of the two maps is equivalent to about 3 days of falling snow. Figure 1 was used to check some suspect 1941–70 stations, and the map of actual mean annual number of snow days was drawn in detail using the isopleths of Figure 1, the contours of a topographic base map and the altitude factor 6·5 days per 100 m. Figure 2 shows a small-scale version of this final map. However, calculations of the mean number of snow

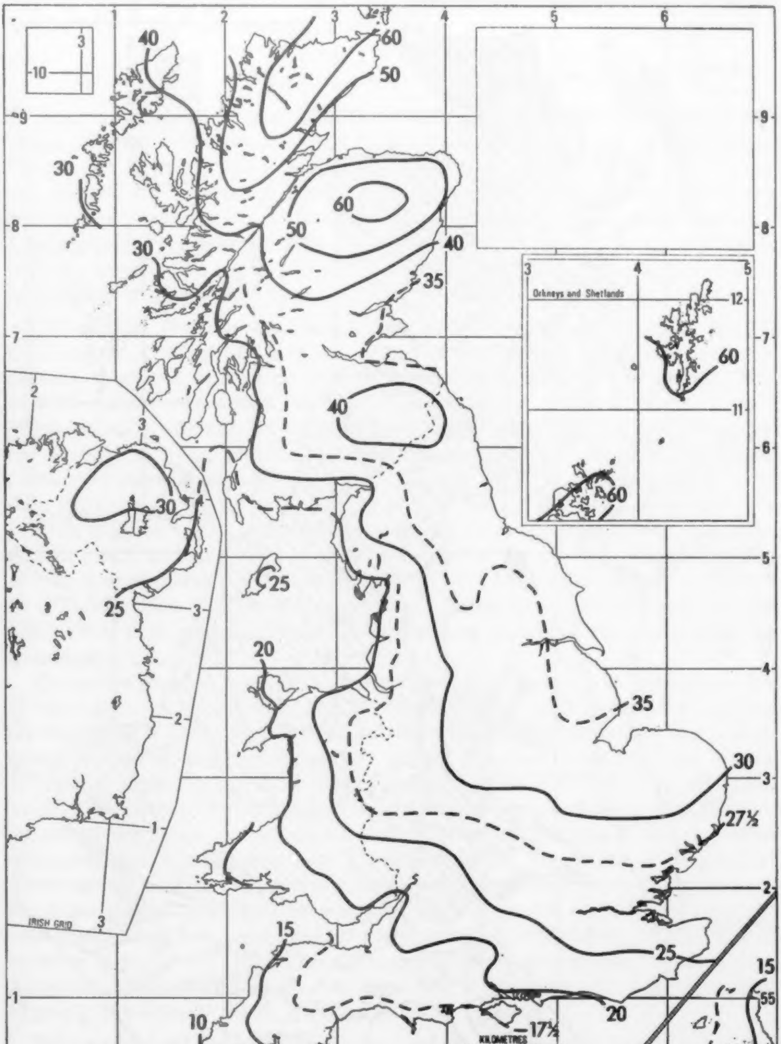


FIGURE 1—MEAN ANNUAL NUMBER OF DAYS WITH FALLING SLEET OR SNOW OBSERVED, 1941–70 ADJUSTED TO A COMMON ALTITUDE OF 100 m BY THE FACTOR 6·5 DAYS PER 100 m

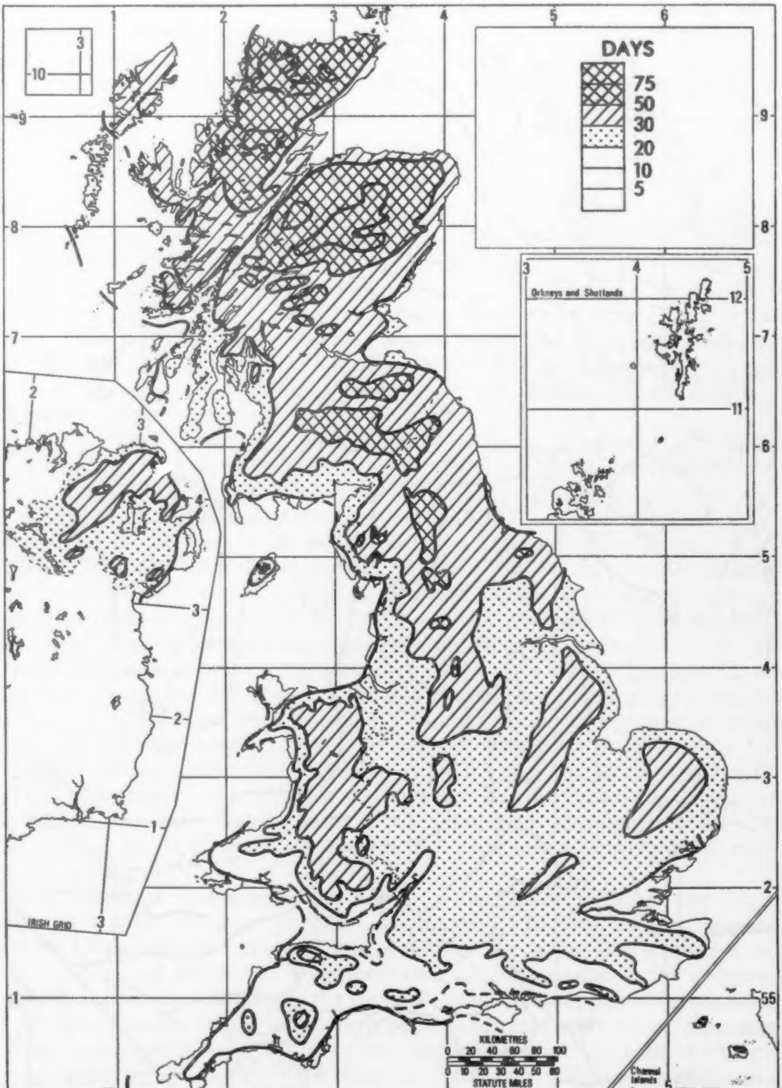


FIGURE 2—MEAN ANNUAL NUMBER OF DAYS WITH FALLING SLEET OR SNOW OBSERVED, 1941–70

(based on Figure 1)

days at any specific point for which the altitude is known should be calculated from Figure 1 and the altitude factor.

3. The annual probability distribution

Ordered annual values were plotted on normal probability paper for a wide range of lengths of record, mostly in the period 1941–70, and at most places form a curve rather than a straight line. When logarithms of the same values are plotted on normal probability paper (equivalent to using log–normal probability paper), some of the stations can be fitted by a straight line, e.g. Eskdalemuir 1941–74, but data from most places seem to fit a distribution between normal and log–normal. As a result, data have not been forced to fit any specific distribution, but are allowed to define their own distribution.

The number of snow days in each winter in the period 1941/42 to 1970/71 at 12 places in Great Britain was plotted on normal probability paper with plotting positions defined by Jenkinson (Meteorological Office, 1975b). Probability curves were drawn for each of these places. From the curve at each place, values of the number of snow days were read off for the median winter, the 5 year,* 10 year, 20 year and 50 year winter with more than the average number of snow days, and the 5 year, 10 year and 20 year winter with fewer than the average, values being estimated from the probability curve.

Each of these values was divided by the mean annual number of snow days at that place, and expressed as a ratio. Data for places with different periods of record were analysed in the same way (e.g. Derry Lodge, near Braemar, 1965/66 to 1973/74, which is 427 m above sea level). Some data from an earlier period, 1881–1915, were also used to confirm the basic shape of the probability distributions.

The ratios from all the places were plotted against the mean annual number of snow days (on a logarithmic scale). Straight lines could be drawn connecting the ratios for a fixed return period for the winters with more than the average number of snow days, while slightly curved lines were fitted for the winters with fewer than average snow days. These lines are assumed to be applicable to all parts of the United Kingdom, and to any period of time. For specified values of the mean annual number of snow days and return periods, ratios were read from the smooth lines on the graph, and are presented in Table II. They can be used as multiplying factors, so that for any place for which only the mean annual number of snow days is known, the number of snow days in a winter can be objectively estimated for a specified probability. In this way an estimate of the probability distribution can be made for any place in the United Kingdom, using estimates of the mean annual number of snow days from Figure 1, the altitude factor, and the ratios in Table II.

Values obtained in this way can be used to map the number of snow days in winters other than the mean. For example, the number of snow days in the 20 year snowy winter is mapped in Figure 3 (in practice it is recommended that the reader calculates the 20 year extreme winter at a point from Table II, not from Figure 3).

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* An *n*-year winter is a winter with a return period of *n* years, i.e. a probability of 1/*n* of being equalled or exceeded in a winter or a year.

FIGURE 3—NUMBER OF DAYS WITH FALLING SLEET OR SNOW EXPECTED IN A 20-YEAR SNOWY WINTER

(1941–70 climatology)

TABLE II—MULTIPLYING FACTORS TO GIVE THE NUMBER OF SNOW DAYS IN A WINTER FOR ANY PLACE IN THE UNITED KINGDOM

Mean annual number of snow days	Un-snowy winters 20-yr	10-yr	5-yr	Median	Snowy winters 5-yr	10-yr	20-yr	50-yr
5	0·10	0·20	0·37	0·80	1·63	2·20	2·68	3·35
10	0·14	0·25	0·43	0·88	1·52	1·97	2·35	2·90
15	0·20	0·31	0·47	0·90	1·45	1·83	2·16	2·64
20	0·26	0·36	0·51	0·91	1·40	1·74	2·03	2·45
30	0·37	0·46	0·59	0·93	1·34	1·60	1·84	2·18
50	0·53	0·61	0·74	0·95	1·25	1·43	1·60	1·84
75	0·69	0·75	0·83	0·98	1·17	1·30	1·42	1·58
100	0·77	0·82	0·86	0·99	1·12	1·21	1·28	1·40
150	0·85	0·89	0·93	1·00	1·04	1·07	1·10	1·14

(Snowy winters are defined as ones with more than the average annual number of snow days, un-snowy winters as ones with fewer.)

4. THE DURATION OF FALLING SNOW AND SNOW ACCUMULATION

A day of falling snow might equally describe a day with a fierce blizzard or one with no more than a few snow grains. Of far more interest than the number of days with snow in a winter are estimates of the number of hours of falling snow, and of heavy falling snow. However, hourly snowfall data are very much more scanty than daily observations, and therefore only approximate conversions can be produced to estimate hourly data from daily data.

For the period 1949/50–1970/71 the number of days with falling sleet or snow was noted for each month at Birmingham (Elmdon) Airport. Also noted was the number of hours when falling snow of any intensity was reported, the number of hours when moderate or heavy snow was reported (water equivalent intensity $\geqslant 0{\cdot}5$ mm h^{-1}), and the number of hours when heavy snow only was reported (water equivalent $\geqslant 4{\cdot}0$ mm h^{-1}).

The number of snow days in each winter was plotted against the number of hours of falling snow in the same winter, and a straight line was fitted through the points by eye. It was assumed that this approximate conversion relationship which had been found by sampling a wide range of winters at one place could reasonably be applied to other parts of the country with different snow climates. It was also found that for every 1000 observations of snow flakes, crystals, grains or prisms (code figures 70–79), there were a further 137 observations of snow showers, and a further 33 of hail showers. These were included in the conversion relationship.

A map was drawn of the estimated mean annual number of hours of falling snow (and hail), by using the map of the mean annual number of snow days (Figure 2), and the conversion relationship from Birmingham, to re-label the isopleths.

Similarly a conversion relationship was found from a graph of the number of snow days in each winter against the number of hours with moderate or heavy snow in the same winter at Birmingham (Table III). For every 1000 observations of moderate or heavy snow (flakes), there are a further 79 observations of heavy or moderate snow shower, and a further 50 observations of moderate or heavy hail shower. The standard error of estimate for the number of hours of moderate or heavy snow at Birmingham by this method is between one and two hours for all values.

TABLE III—CONVERSION RELATIONSHIP FOR THE NUMBER OF HOURS OF MODERATE OR HEAVY FALLING SNOW, BASED ON AN ANALYSIS OF BIRMINGHAM DATA

Number of days in a winter with snow falling	5	10	20	30	50	75
Number of hours of moderate/ heavy snow	1·5	4·5	10·0	16·5	30	48

A map of the estimated mean annual number of hours with moderate or heavy falling snow may be drawn (Figure 4) using the map of Figure 2 and the conversion relationship for moderate or heavy snow given in Table III. Figure 4 gives an estimate of the number of hours in an average winter when snow is falling at a rate greater than a water equivalent of about 0·5 mm h^{-1}, which is on average an accumulation rate of lying snow of greater than 0·5 cm h^{-1}. It is not possible to give a quantitative measure of the accuracy of the estimates from Figure 4; the relationship derived for Birmingham has been assumed to apply anywhere in the UK.

Despite the approximations involved, the method was further extended to produce a tentative map of the number of hours with moderate or heavy falling snow in a 5 year and in a 20 year winter. The 5 year and 20 year values of the number of snow days are obtainable from Sections 2 and 3. These are then converted into hours of moderate or heavy snow by the conversion relationship of Table III.

The number of hours with moderate or heavy falling snow in each winter at Birmingham (but excluding showers and occurrences of hail) were ordered and plotted on normal probability paper. The probability estimates from the plot are given in Table IV.

TABLE IV—THE NUMBER OF HOURS WITH MODERATE OR HEAVY FALLING SNOW IN A WINTER AT BIRMINGHAM

Probability (per cent)	75	50	25	10	5	2
Number of hours exceeded in a winter	7·5	14	22·5	30	35	40

Snow depths reported at Birmingham (Elmdon) and Eskdalemuir every 3 hours in the 12 winters 1964–75 were examined, and the depths of snow which accumulated in 3 hour, 6 hour, 12 hour and 24 hour durations were noted. The frequencies of various depths were plotted against duration (on a logarithmic scale). Smooth curves were drawn connecting fixed return periods, and the depths were also smoothed between the return-period lines by using probability paper. Snow-depth accumulations read from the graph for several durations are given in Table V.

TABLE V—SNOWFALL ACCUMULATIONS (cm) IN SPECIFIED DURATIONS AND WITH SPECIFIED RETURN PERIODS AT BIRMINGHAM (ELMDON)

Duration (hours)	Frequency (per year)		Return period (years)		
	2	1	2	5	10
1	1·9(3·2)	3·4(4·3)	4·6(5·3)	6·6(6·6)	8·5(8·5)
3	3·2(5·1)	4·8(6·8)	6·5(8·3)	9·2(9·9)	12·7(12·8)
6	3·6(6·3)	5·7(8·3)	7·5(10·4)	10·5(12·5)	15·4(16·2)
24	3·9(8·5)	7·3(11·2)	9·5(14·7)	13·6(19·0)	20·8(23·8)

Values for Eskdalemuir are given in brackets.

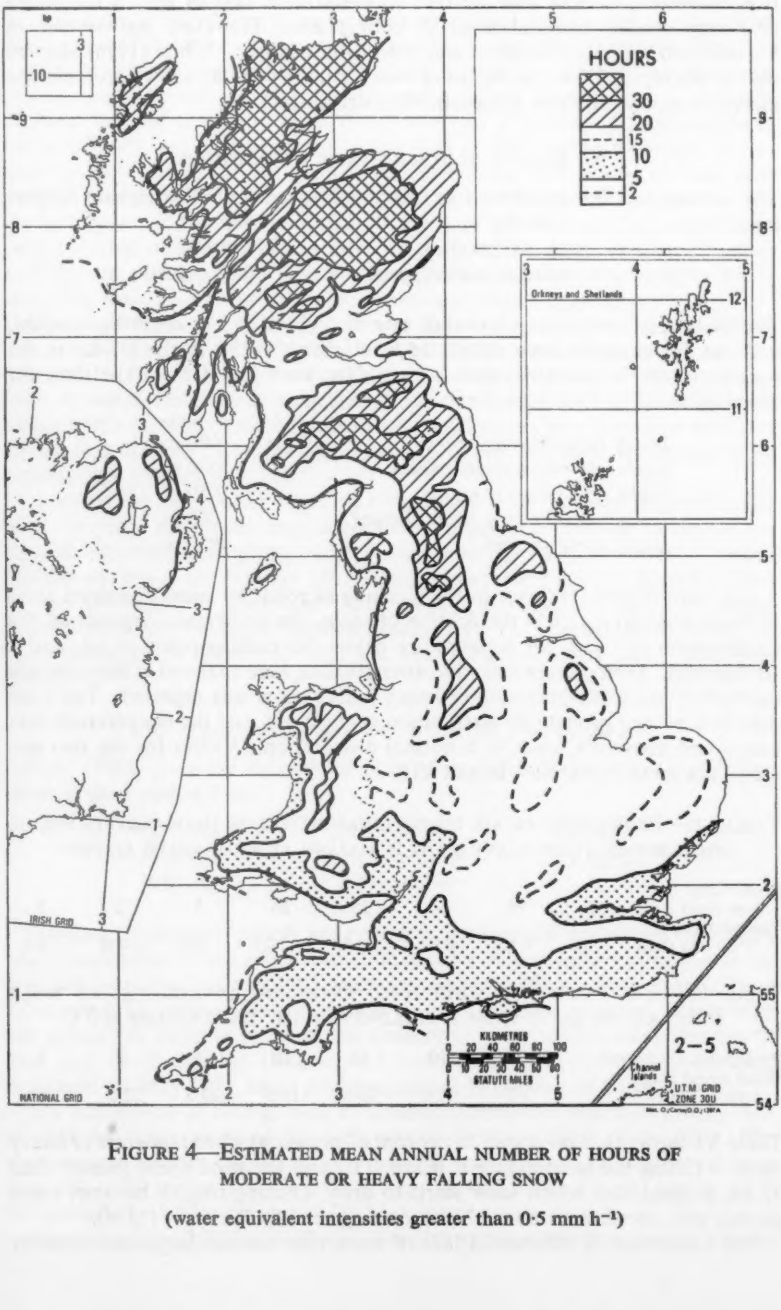

FIGURE 4—ESTIMATED MEAN ANNUAL NUMBER OF HOURS OF MODERATE OR HEAVY FALLING SNOW

(water equivalent intensities greater than 0·5 mm h^{-1})

It is interesting to note that the rare short-duration falls of only a few hours give very similar accumulations at both places. However, snowstorms at Eskdalemuir are more frequent and tend to last longer. White (1974) showed that in Michigan, USA, for depths of over 3 cm the one-day snow accumulation increases exponentially as the probability decreases.

5. Snow and other weather conditions

The average weather conditions in heavy falling snow at Birmingham Airport are:

visibility	700 m
air temperature	−0·1°C
wind direction/speed	030°, 10 kn.

The close relation between snowfall rate and visibility has often been noted, and has, for example, been calculated by Richards (1954) in the USA. In the present study the median values of visibility were found from the data for Birmingham (Elmdon) Airport:

	visibility
heavy non-showery snow	690 m
moderate non-showery snow	1080 m
slight non-showery snow	2650 m
moderate or heavy snow shower	1660 m
slight snow shower	4800 m.

The most important factor in the blocking of roads by snow in upland areas of the United Kingdom is the drifting of snow. Its occurrence depends on the combination of snow, air temperature below the melting-point of ice, and a strong wind. Temperature and wind-strength data were analysed at Birmingham (altitude 97 m) when moderate or heavy falling snow was reported. The wind data fit a normal probability distribution very closely, and the temperature data below and above 0°C each fit a normal distribution. Values for the two elements are given in Tables VIa and VIb.

Table VIa—Probability of air temperature being less than certain values when moderate or heavy snow is falling at Birmingham Airport

Probability (per cent)	90	75	50	25	10	5	2	1
Temperature (°C) less than	0·82	0·50	0·03	−0·89	−2·25	−3·10	−4·0	−4·6

Table VIb—Probability of wind speed exceeding certain values when moderate or heavy snow is falling and the temperature $\leqslant$0°C

Probability (per cent)	75	50	25	10	5	2	1
Wind speed (kn) greater than	8·5	12·0	15·5	18·5	20·5	22·5	24·0

Table VI shows that on about 25 per cent of occasions when moderate or heavy snow is falling the temperature is below 0°C, and the wind speed greater than 12 kn, a speed near which snow starts to drift. Drifting usually becomes more serious with speeds over about 17 kn, as suggested by Richards (1954).

The occurrence of substantial falls of snow with various large-scale weather

patterns has been discussed by Lowndes (1971). He found that most of the 562 substantial snowfalls (water equivalent greater than 7 mm in 24 hours) in the years 1954–69 were associated with either a warm front or warm occlusion approaching from between south and west (260 cases), or a polar low or trough in a northerly airstream (180 cases). Lowndes's data show that substantial falls of snow associated with a warm front or warm occlusion approaching from between south and west occurred in any part of the country with similar frequency, most places on low ground having had between 3 and 10 such falls in the 15 winters. However, near the east coast of England and over north Scotland polar lows or troughs in a northerly or easterly airstream gave more than 10 substantial snowfalls in any one place. The same weather situation over the rest of the country gave very many fewer substantial snowfalls. These facts give some insight into the distribution shown in Figure 1.

Clarke (1969) analysed the number of days with any snow or sleet falling over south-east England, 1954–69, and classified them according to the weather pattern. He found that the most common weather situations were (a) a warm front or warm occlusion approaching the station (113 cases), (b) snow showers with a north-easterly or easterly surface wind (90 cases), (c) a polar low or minor trough in a northerly type (64 cases) and (d) a polar low or minor trough in an easterly type (63 cases).

Many of the most severe blizzards experienced over southern England in the past 100 years have been associated with a depression moving slowly up the English Channel and giving very strong easterly or north-easterly winds. Notable examples are January 1881—central southern England, March 1891—south-west England, December 1927—south-east England and December/January 1962/63—southern England (Jackson 1977). Further north, however, the weather types associated with the heaviest snowstorms have been more varied.

6. Probability of snow with the time of year

Manley (1969) gives the mean dates of the first and last observations of falling snow in the London area:

1871–1900	23 November	12 April
1901–30	25 November	15 April
1931–60	8 December	1 April.

Summer snowstorms which are reported occasionally are almost invariably heavy hailstorms. The earliest authentic date for falling snow in London in the past 100 years (see Jackson 1977) is 25 September in 1885, and the latest date is 2 June in 1975. Some noteworthy snowstorms have been recorded on relatively low ground in different parts of the country in every month from October to May (e.g. 19–21 October 1880, snow 3 inches deep at Croydon, 5 inches deep at Exeter; 18 May 1891, snow 6 inches deep at Norwich and Daventry).

The occurrence of falling snow in London (Greenwich and Kew) from 1859 to 1958 has been analysed for each pentad (5 day period) of the year. The snowiest pentad was 20–25 February with 90 snow days. The number of snow days fell to 40 in the pentads 7–11 December and 27–31 March, and to 10 in the pentads 7–11 November and 26–30 April.

Analysis of the distribution of snow days between the various calendar months

in the period 1941–70 is given in line 1 of Table VII.

TABLE VII—MONTHLY DISTRIBUTION OF SNOWFALLS IN THE UNITED KINGDOM (%)

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	Year
Distribution of snow days at an average station, 1941–70	<1	6	15	26	28	17	6	<1	100
Distribution of snow days in London	1	5	16	26	21	22	8	1	100
Distribution of hourly observations of snow at Birmingham	0	3	18	25	37	14	3	0	100
Distribution of heavy snowfalls over UK (after Lowndes)	0	6	20	25	29	16	4	0	100

The results varied slightly between places in the north and south of the country: both November and April ranged from 5 per cent in southern England to 9 per cent in northern Scotland, whilst January ranged from 29 per cent in southern England to 21 per cent in northern Scotland. The distribution of snow days in London, 1714–1896, was analysed by Mossman (1897), and is given in line 2 of Table VII.

Analysis of the hourly data at Birmingham Airport 1949/50 to 1970/71 (line 3 of Table VII) shows a similar distribution between the months, but with slightly larger percentages in midwinter and slightly smaller ones in autumn and spring. (It was interesting to note that the number of hours of falling snow in each individual month at Birmingham seemed to fit a normal probability distribution for values over 10 hours.)

Lowndes (1971) shows the number of occasions when over 7 mm water equivalent fell in 24 hours at any of 41 places in the United Kingdom in the period 1954–69. Percentage values from his analysis are given in Table VII (line 4), and are also very close to the other distributions in Table VII.

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APPOINTMENT

Dr B. J. Mason, C.B., F.R.S., the Director-General of the Meteorological Office, has been appointed senior Vice-President and Treasurer of the Royal Society for a five year period commencing 1 December 1976. He succeeds Sir James Menter. In this post he will be involved in policy-making over a wide field and responsible for administering all the Society's funds and grants.

NOTES AND NEWS

Retirement of Mr G. R. R. Benwell

Mr George Richard Raymond Benwell, who retired on 21 December 1976, joined the Office as a Technical Officer in September 1937 after graduating with a B.A. degree in Mathematics at Oxford University. After some initial practical experience at Kew Observatory and attendance at the Training School at Croydon Airport and South Kensington he joined the climatological branch for work connected with the British Rainfall Organization and the Inland Water Survey. He remained in that branch until the outbreak of the Second World War. Towards the end of 1939 he went to Linton-on-Ouse (Headquarters No. 4 Bomber Group) and received a commission as a Flight Lieutenant in the Royal Air Force Volunteer Reserve in April 1943. He stayed at Linton until 1944 and then had shorter spells of duty at CFO Dunstable, Headquarters Bomber Command, No. 5 Group and Tiger Force until he returned in September 1945 to Dunstable. He was demobilized from the RAFVR in April 1946 and promoted to Senior Scientific Officer in 1948 but he remained at Dunstable until early 1949 when he was posted to Habbaniyah for a tour of duty. He was promoted to Principal Scientific Officer whilst at Habbaniyah where he stayed until 1951 when he returned once again to Dunstable, and he stayed there until late 1961 when the units at Dunstable moved *en bloc* to the present Headquarters at Bracknell. During 1962 to 1964 he was engaged in synoptic research in Met 0 12 and when that branch was reorganized at the end of 1964 he transferred to Met 0 11 to continue work in forecasting research for a further eight years. In 1973 he was promoted to Senior Principal Scientific Officer, was appointed Assistant Director (Central Forecasting) and occupied that post until his retirement.

Dick Benwell has had a very long career which has been characterized by relatively few postings compared with the careers of many of his colleagues who also joined in 1937. A spell of over four years at one unit (Linton) during the war must be almost a record, and over his career as a whole he has spent a large part of his working life in the Central Forecasting Office and in research associated with synoptic meteorology. His very wide experience in these practical aspects has been of very great value to the Office and he drew substantially on this experience during his work in forecasting research.

Although Dick and I attended the same training courses in 1937 our official business and work were such that we did not work closely together as colleagues until the final year of our last postings. Dick's good humour, willingness to help, ability to co-operate with others, wide experience of practical forecasting,

dedication and conscientiousness have been greatly appreciated by many of his colleagues for much of his long career and not least by me during this last year.

Their numerous friends will wish Dick and his wife Dorothy a long and happy retirement and hope that they enjoy good health to enable them to follow their interesting activities for many years to come.

N. BRADBURY

HALLEY LECTURE

The University of Oxford has invited Dr B. J. Mason, the Director-General of the Meteorological Office, to give the Halley Lecture on 17 May 1977. The subject of his lecture will be 'The Atmosphere of the Planets'.

OBITUARY

It is with regret that we have to record the death on 21 September 1976 of Mr H. E. Atkinson, Assistant Scientific Officer, of the Port Meteorological Office, Cardiff.

CORRECTIONS

Meterological Magazine, October 1976, page 296.
The sixth line below Table II should read

Mean: $\overline{x} = 234{\cdot}2$ mm.

The eighth line below Table II should read

Coefficient of variation CV: $= 100\ S_x/\overline{x} = 37{\cdot}9$.

Meteorological Magazine, November 1976, page 359. The title of the book reviewed should have read '*Climate and the environment—the atmospheric impact on man*' and not '... *of man*' as printed.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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